

Solar Telescopes and Instruments: Space

The first solar space observations

Fifty years of development in solar space instrumentation have demonstrated the close relation between technical and scientific progress.

Solar physics from space, and indeed space astronomy, started in 1946 in the United States, when captured V-2 rockets, capable of rising 160 km above the ground, became available for use as free-flying, high-altitude laboratories. It was not surprising under these circumstances that a group from the US Naval Research Laboratory (NRL) in Washington, DC under Richard Tousey became the first to make use of the fortunate opportunity.

An initial attempt was made on 28 June 1946 to observe radiation in the hydrogen Lyman alpha line from the Sun. However, the camera was never retrieved from the crater made when the V-2 impacted on the desert floor of the White Sands Missile Range in New Mexico. The next attempt, on 10 October 1946, was a success, giving us the first ultraviolet spectrum of the Sun, 220–340 nm (nm—nanometer, i.e. 10^{-9} m), shown in figure 1. At altitudes above 55 km, rising through the ozone layer, the solar spectrum appeared all the way down to 220 nm. The first observations of solar x-rays followed in 1949 when Herbert Friedman, also of NRL, flew a payload of Geiger counters on a V-2 rocket (see also [ROCKETS IN ASTRONOMY](#)).

Further rocket observations in the 1950s established that the Lyman alpha line of hydrogen was emitted from the solar CHROMOSPHERE. The radiation in this line was measured quantitatively in 1949 on the same flight that detected solar x-rays and also measured the Schumann ultraviolet continuum at 142.5–160 nm. The line profile of Lyman alpha was measured later, and the narrow absorption core at its center, detected in 1959, established the presence of an extended geo-corona. The first solar spectrum below Lyman alpha was recorded in 1960. Emission lines at these short wavelengths were classified as lines from high ionization stages, mainly of iron, and shown to come from the hot coronal plasma at 1.5–2.5 MK (MK—megakelvin, i.e. million kelvins). The strong enhancement of x-ray emission during solar flares was detected in 1956. When a rocket was flown during a solar eclipse in 1958, it was determined that solar x-rays originated in the CORONA, particularly above ACTIVE REGIONS. The first image of the Sun in x-rays was recorded in 1960, using a pinhole camera on board a rocket. Finally, it may be mentioned that the first CORONAGRAPH was flown in space in 1963.

Looking back it is amazing that these early days of rocket experiments and our first established, simple knowledge about the ultraviolet and x-ray emission from the Sun are only 40–50 years behind us. The early discoveries are now so familiar that we hardly reflect on how difficult they were to obtain and on the fact that they were not obvious.

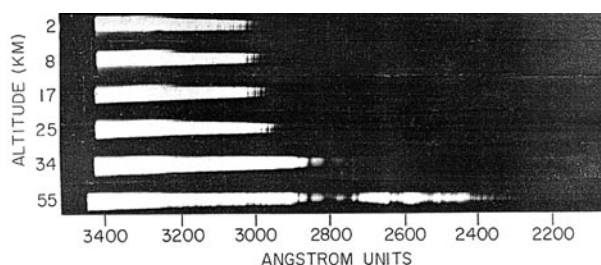


Figure 1. The first ultraviolet spectrum of the Sun. Recorded on a V-2 rocket flight on 10 October 1946.

Early technical developments

Technical developments in many fields conditioned the early progress. Contributions to these developments came from universities and research laboratories in the US, France and the UK.

Magnesium fluoride lenses, transparent to 110 nm, were used in the first rocket observations. Development of mirror coatings with high reflectivity in the far ultraviolet was, however, crucial for progress beyond the first simple experiments. Oxidized aluminum, used on mirrors in the visual wavelength range, does not reflect radiation at far-ultraviolet wavelengths. However, fresh unoxidized aluminum is an efficient reflector down to 100 nm. The solution was to coat the fresh aluminum with a layer of magnesium fluoride. This stopped oxidation and preserved the high reflectivity. Below 110 nm other reflecting materials were found, notably gold, used in instruments on ORBITING SOLAR OBSERVATORIES (OSOs) (see below) and Skylab, but also osmium and silicon carbide. Today, multilayer mirror coatings can be produced with reflectivities up to 30% in narrow ultraviolet and x-ray wavelength bands.

Another important concern is to avoid contamination by stray light. The Sun radiates the overwhelming part of its energy in the visual spectral region. Even a small fraction of this light scattered off the instrument surfaces will completely swamp the ultraviolet signal that we want to study. This problem was solved when an aluminum filter, consisting of a freely suspended aluminum foil of 100 nm thickness, was developed in France and the US. The filter reflected visual light but was transparent to ultraviolet radiation.

Detector development was no less essential. In the 1950s and 1960s Kodak increased the sensitivity of their ultraviolet-sensitive Schumann emulsions, originally developed around 1900. In these emulsions the silver halide grains are sticking out of the gelatin layer to avoid absorption of ultraviolet radiation in the gelatin. This makes it sensitive to mechanical pressure and a roll film camera that could hold large amounts of this film was not made until the 1980s for the High Resolution Telescope and Spectrograph (HRTS), on Spacelab 2. Indeed, since photographic film quickly records vast amounts of image data, it has continued to be used almost until this day.

Photoelectric detectors were used in the near ultraviolet in instruments flown on rockets already in 1952. Channel electronic multipliers came into use with the first satellite instruments. Array detectors in two dimensions proved difficult to make for ultraviolet wavelengths. The first spectral and image scans were therefore made with pinhole devices. This meant slow scans and low time cadence for images and spectra. A modern solution is to convert the ultraviolet radiation to visual light before it is registered with a conventional CCD.

The years of early rocket and satellite experiments also saw the development of increasingly accurate pointing systems. The first rockets flew without pointing and for some time instrument resolution did not put any stringent demands on pointing accuracy. However, it became obvious that much of the extreme ultraviolet and x-ray emission is concentrated in active regions a few arcminutes in extent consisting of even smaller structures. Thus, good instrument resolution and pointing became decisive in order to make any sense of the observations.

A biaxial pointing system, stable in pitch and yaw, was designed by the University of Colorado in 1954 and improved versions were used for all ultraviolet and x-ray observations in the subsequent decade. A triaxial pointing system, developed at the Atomic Energy Research Establishment in England in 1965, prevented variations in roll. Pointing could now be stabilized to 2 arcsec. Today pointing stability is better than 1 arcsec on modern satellite platforms.

In this perspective satellite observatories may be regarded as a final step among the early technical developments. The first decade of satellite observatories saw increased sophistication in satellite platforms as well as in instrumentation. Space solar physics outgrew its beginnings and reached maturity with the instruments on the Apollo Telescope Mount on Skylab in 1973–4.

Satellites, balloons and rockets in the 1960s

The first registration of solar ultraviolet and x-ray radiation using instruments on a satellite came on the Soviet Sputnik 2 in 1957. The first US satellite with solar instruments, Vanguard 3 in 1958, was a failure. However, close observations of its orbit led to the discovery of the expansion and contraction of the Earth's ionosphere caused by diurnal and long-term variations in the solar ultraviolet and x-ray emission.

Solrad 1, launched in 1960, was the first in a series of satellites observing various wavelength bands in ultraviolet and x-rays. These satellites provided long-term coverage of wavelength and intensity changes of the solar radiation until 1976. Solrad demonstrated the strong solar variability in x-rays compared with the much lower variability in the ultraviolet. The satellite instruments did not have imaging capabilities in x-rays, but observations during the solar eclipse in 1966 showed that the solar x-ray emission was concentrated in small regions, less than 1 arcmin in diameter, i.e. the hot cores of active regions.



Figure 2. Model of the OSO satellites. OSOs 1–7 all looked similar.

1962 saw the beginning of a new series of solar satellites, the OSO missions (figure 2). The intent was to follow the Sun through an entire 11 year cycle with nearly identical ultraviolet and x-ray instruments. The OSO satellites had three axis-stabilized platforms. Pointing stability exceeded the imaging quality of the scientific instruments, but solar imaging was possible with a resolution of about 1 arcmin for the earliest OSOs. Studies could be made of coarse active region structures and of emission associated with the solar supergranulation in several spectral lines formed at different temperatures. OSO-8 (1975–78), the last in the series, came after Skylab (1973–4), differed from the earlier OSOs and is mentioned below.

Rocket experiments continued after 1960 in the US and in other countries. In France we may note the rocket and balloon flights in the 1960s and early 1970s that carefully measured the solar ultraviolet radiation from ~ 200 nm down to Lyman alpha at 121.6 nm and its variation from Sun center to limb. The solar spectrum at these wavelengths comes from the upper photosphere, the lower part of the chromosphere and the temperature minimum layer between them. The strong discrepancy, as much as a factor of 10 at wavelengths of 150–180 nm, between the observed and theoretically calculated intensities inspired improved efforts at modeling these layers in the solar atmosphere. The lowest observed radiation temperature in the ultraviolet continuum at 150 nm was much discussed. Successive experiments found different results. This was not trivial since the value of the minimum temperature on top of the photosphere was considered to be connected to the amount of non-thermal energy passing from the photosphere to the corona and heating the corona.

The UK launched its first satellite for solar research, ARIEL 1, in 1962. Ariel 1 carried instruments that measured the solar spectrum in x-ray wavelengths, 0.4–1.4 nm. The enhancement of the solar x-ray intensity by factors of 10 or more during SOLAR FLARES was recorded on many occasions. This was of great interest at the time for

understanding the enhanced ionization in the D-layer in the Earth's ionosphere during flares, leading to disruption of radio communications. Groups in the UK also took part with far-ultraviolet and x-ray instruments in the OSO program, i.e. OSO-4, -5 and -6, leading up to their later strong participation in SMM, Yohkoh and the Solar and Heliospheric Observatory (SOHO).

The UK Skylark rockets launched several ultraviolet instruments starting in 1964. In 1968 they obtained for the first time spectra of both the solar limb and the disk in the spectral range 150–220 nm. These observations were aimed at deriving the temperature structure of the outer solar atmosphere at $\sim 100\,000$ K using a method that did not rely on uncertain instrument calibration, atomic cross sections or element abundances. Grazing incidence observations at shorter wavelengths, 15–80 nm and 1.5–5 nm, were added to study the corona at temperatures of 1 MK or more.

Slitless spectrographs launched into the total solar eclipse on 7 March 1970 by British and US investigators revealed that the emission from spectral lines emitting at temperatures of 10 000–300 000 K was not limited to a range in altitude of a few tens of kilometers as predicted by theoretical models, but extended over more than 1000 km. The true significance of this observation did not, however, make a strong impression at that time.

Finally, one might mention two tests of the NRL ultraviolet spectrometers, SO82A and SO82B, on Skylab. The test rocket for SO82A was launched during a solar flare on 4 November 1969. For the first time the small hot kernel of a flare was revealed. It was only a few arcseconds across and it showed up in highly ionized iron lines emitting at temperatures of several million kelvins. The corresponding test flight for SO82B in August 1970 led to the first published measurement of the large non-thermal widths of lines formed around 100 000 K, pointing to the presence of strong dynamics and waves in the transition region between the solar chromosphere and corona.

Early observations of the spectral region 20–150 nm showed that it contained a number of emission lines. Many of these lines had been identified and absolute intensities had been established. Analysis techniques had been developed in response to the new observations, to determine plasma densities and temperature structure of the emitting layers. In the resulting models the temperature above the chromosphere rose sharply from 10 000 K to 300 000 K in only about 100 km. It was at first not recognized that this result disagreed strongly with the observation that solar plasma in the 100 000 K range extended several thousands of kilometers above the chromosphere.

Skylab

SKYLAB is covered in a separate article in this encyclopedia and will only be described briefly here. The Skylab instruments were much larger than the corresponding OSO instruments. Angular resolutions in x-ray and

extreme ultraviolet approached 2–4 arcsec. These high-resolution pictures showed that the solar transition region and corona are built up by magnetic loops containing the hot solar plasma. Solar flares occurred in the loops and the high-temperature components of flares were detected, having temperatures up to 20 MK. Loops and prominences were seen to tear loose from the solar surface to form what have later been termed coronal mass ejections (CMEs). CORONAL HOLES, extended regions where the emission in spectral lines from the corona was strongly depressed, were discovered and the occasional fast solar wind near the Earth, with wind speeds twice as high as the 'normal' solar wind, was found to be coming from the equatorial coronal holes. It was recognized that the Sun might have more permanent polar coronal holes.

Skylab missed out on dynamics and rapid time variability. Observations could be made only on a limited supply of photographic film or the photoelectric scans of wide fields of view took too long a time. Thus, high-cadence observations of loop structures were few. The Skylab spectrometers also lacked combined good spectral and spatial resolution. Thus, they could not detect the high velocities, 40–100 km s⁻¹, commonly occurring in the 100 000–500 000 K temperature range now observed with the ultraviolet spectrometers on the Solar and Heliospheric Observatory (SOHO).

Modern rockets and satellites

Many advanced instruments have flown in the more than 25 years, since Skylab. The Soviet Union had solar instruments on several satellites, an early example being OST-1, on Salyut 4 in 1975. This far-ultraviolet telescope, constructed by the Crimean Astrophysical Observatory, obtained new characteristics of plages and solar flares.

The Japanese Astro A, also known as HINOTORI, was launched in 1981. Its main objective was the detailed study of solar flares. One of its instruments imaged flares in x-rays, at energies of 10–40 keV or around 0.1 nm wavelength. Another instrument performed spectroscopy of x-ray flares in the wavelength range 0.17–0.2 nm, using a Bragg spectrometer. Investigations recorded the time profile and spectrum of x-ray flares and looked for gamma rays from flares at energies from 0.2 to 9.0 MeV. Hinotori was a forerunner for Japan's highly successful solar x-ray satellite, YOHKOH, launched in August 1991 and still in operation.

Orbiting Solar Observatory 8

OSO-8 was launched in June 1975 and operated until September 1978. It was the first solar satellite to attempt observations of the solar atmosphere with simultaneous high spatial and spectral resolution. It was also the first satellite to operate on a near-real-time basis with the science teams on the ground. It had two pointed instruments: an ultraviolet spectrometer, wavelengths 120–200 nm, and a multichannel ultraviolet and visible polychromator with six wavelength channels. These channels registered the strong resonance lines from singly

ionized calcium and magnesium and the Lyman alpha and beta lines from hydrogen. The wavelength border regions of the channels contained visual and ultraviolet continua and the lines from doubly ionized silicon at 120.6 nm and five-times ionized oxygen at 103.2 nm. Thus, the instruments could study the solar plasma at temperatures from 6000 K to 250 000 K, i.e. the chromosphere and lower transition region. Spectral resolutions ranged from 2 to 10 pm (pm—picometer, i.e. 10^{-12} m). The best possible angular resolution of both instruments was 1–2 arcsec. However, the slit spectrometer took most of its data with a 2 arcsec \times 20 arcsec slit and the multichannel instrument was mainly run in a coarse mode with 10 arcsec resolution. These two instruments were built and operated by the University of Colorado and the French National Space Agency, CNRS, respectively.

OSO-8 demonstrated that the energy in the 150–300 s oscillations was several orders of magnitude lower than the radiative losses from the upper solar atmosphere. Thus, the solar corona could not be heated by acoustic waves, the most commonly held view at the time. Persistent redshifts in lines emitted from the transition region, equivalent to down-flow velocities of ~ 10 km s $^{-1}$, were also recorded for the first time. Since flows of this magnitude will drain the corona of gas in a few minutes, alternative explanations have been sought. The most promising involve disturbances generated near the top of magnetic loops by processes heating the corona, then progressing downward along the loop legs. Similar redshifts have been noted in stars and may be a general property of stellar atmospheres.

High Resolution Telescope and Spectrograph

The High Resolution Telescope and Spectrograph (HRTS) (figure 3) had the high angular resolution not realized with OSO-8. HRTS was built and operated by the US Naval Research Laboratory and flew on 10 rocket flights between 1975 and 1997 and was a part of Spacelab 2 in 1985. On most flights the spectrograph operated at wavelengths between 117 and 170 nm, covering the full range or registering selectable narrow bands, 1.4 nm wide, centered on strong emission lines. HRTS was the first ultraviolet spectrograph with stigmatic imaging of an extended slit, 1000 arcsec long, at high angular resolution (1 arcsec).

HRTS made several important discoveries. Notable are the detection of explosive events on the first HRTS flight and the investigation into the possibly small filling factors for the emission in the solar atmosphere. Explosive events are small regions, with diameters of ~ 2 arcsec, with a velocity dispersion amounting to ± 100 km s $^{-1}$. They are seen in the 100 000 K plasma and last typically 1 min. They could be caused by magnetic reconnection in the solar atmosphere and may thus be the observational signature of one of the main mechanisms proposed for heating of the solar corona.

The study of filling factors with HRTS was made possible by the good spatial resolution of the instrument and its spectral coverage that included density sensitive



Figure 3. The HRTS, flying on the space shuttle as part of Spacelab 2, July–August 1985. HRTS is the long tube to the right in the figure.

line pairs. From the derived densities, the total emission, and the overall size of the emitting structures it was concluded that only a small fraction of the volume is filled with plasma, i.e. filling factors amount to between 1% and 0.01% of the total volume of the structures.

HRTS also discovered that rapid down-flows of plasma in the transition region over sunspots are common, with in-flow velocities of 50–100 km s $^{-1}$ or more. Another discovery was that transition region line profiles frequently have a multiple structure as if several distinct and different velocities exist inside the 1 arcsec resolution element of HRTS. This could be connected to the low filling factors if dynamic conditions are different in the small substructures that the transition region may consist of. Finally, clear connections were discovered between line intensities, wavelength shifts and line widths, and the underlying photospheric magnetic fields. The relation between fields and line shifts is asymmetric for red- or blueshifted profiles. A probable reason for an asymmetry would be if waves running in one predominant direction are present in the transition region.

Solar Maximum Mission

The SOLAR MAXIMUM MISSION (SMM) satellite (figure 4) was launched in February 1980. The primary goal was to make coordinated studies of solar activity, particularly solar

flares and eruptions, at a period of high solar activity. Over less than 10 years SMM observed more than 12 000 flares and over 1200 eruptions, called CMEs. The history of SMM was at times dramatic. The attitude control system of the satellite malfunctioned in January 1981 but was repaired in orbit in April 1984 and SMM continued observing until November 1989.

Four of the instruments on SMM registered the energetic solar radiation from gamma ray energies to soft x-rays. These instruments measured the spectral intensity of flares continuously over several years. A comprehensive set of coordinated data on this phenomenon was collected, throwing new light on all kinds of flare processes and on solar activity in general.

The Gamma Ray Spectrometer (GRS) provided gamma ray flare intensities as a function of time as well as the spectral distribution of the radiation. The Hard X-ray Burst Spectrometer (HXRBS) observed time series of hard x-ray bursts from flares in 15 energy channels between 20 keV and 260 keV (1 keV corresponds to a wavelength of 1.23 nm; higher-energy photons have proportionally shorter wavelengths). Thus spectra of the bursts could be built up. Continuous observations were made with a time resolution of 128 ms, but shorter intervals were possible. The soft X-ray Polychromator (XRP) monitored individual emission lines that are strong in active regions and flares. The selected lines give information on temperature, density, velocity, element abundance and non-equilibrium states in the flare and active region plasma. The Hard X-ray Imaging Spectrometer (HXIS) delivered simultaneous images of solar flares in six energy bands between 3.5 keV and 30 keV. The instrument had a coarse field of view corresponding to the size of an active region, with a spatial pixel of 32 arcsec, and a high-resolution field of view centered in the coarse field, with a spatial pixel of 8 arcsec. Time resolution could be automatically varied from 1.5 s in the early stages of a flare to 7 s in the decaying phase. Except for HXIS, which ended its life in November 1980, the high-energy instruments lasted until the end of the mission.

SMM also had three low-energy instruments that supported the studies of flares and solar activity. The Ultraviolet Spectrometer and Polarimeter (UVSP) produced monochromatic raster images at any wavelength between 115 nm and 360 nm with selectable wavelength bandwidth and angular pixel size down to 1 arcsec \times 1 arcsec. Images in four lines could be observed simultaneously, or wavelength bands might be placed in the opposite wings of lines to measure Doppler shifts (i.e. velocities) or make polarization measurements. Time cadence for observations with a single pixel could be a fraction of a second. However, in most practical situations it took several minutes to build up a raster image. In April 1985 the UVSP grating drive failed. Observations were still possible but only at a fixed wavelength around 138 nm.

A main objective of UVSP was to study the flare plasma at temperatures below 200 000 K in the transition region lines available in its spectral range. However, all



Figure 4. The SMM satellite. The aperture openings for the instruments are visible in the front plate. An astronaut is working on the satellite.

types of solar features were studied: prominences, solar active regions, sunspots, the quiet Sun. An interesting attempt was made to observe explosive events and relate them to solar magnetic fields. Since they have short lifetimes, explosive events might come and go in less time than it took to record a UVSP raster. Explosive events have a considerable velocity dispersion and could be detected by registering strong intensity variations in the far wings of the 154.8 nm line emitted at 100 000 K. Explosive events and other micro-flaring activity were found to be located in areas where magnetic fields of opposite polarity came close together and could well be caused by magnetic reconnection.

The High Altitude Observatory Coronagraph/Polarimeter on SMM produced images of a selected quadrant of the corona in the range from 1.6 to 6 solar radii with a spatial resolution of 10 arcsec set by the detector pixel size. Observations in seven wavelength bands in the visual spectral range made it possible to distinguish between various features of the solar corona and discriminate between ejected plasma at coronal and chromospheric temperatures. A major outcome of this instrument was a long-term study of CMEs and their relation to solar activity. SOLWIND, operating from March 1979 to September 1985, carried a similar coronagraph, also adding to our knowledge of coronal structure and dynamics.

CMEs were first detected with the coronagraph on OSO-7 and were routinely observed on Skylab. It soon became obvious that CMEs were the cause of strong gusts in the solar wind affecting the Earth's magnetosphere, causing beautiful polar auroras, but also potentially damaging effects to telecommunications and electric power transmissions. The SMM coronagraph had much better time coverage than Skylab, 87% for SMM

against 38% for Skylab. This allowed thorough statistical investigations of the connection between CMEs and solar activity, such as flares and eruptive prominences. Studies found that only half of the CMEs were clearly related to recognized active phenomena. Of the CMEs with such relations 40% were associated with flares, but more than 70% were associated with eruptive prominences. The measured average CME velocities were furthermore considerably lower than those found previously from Skylab. These new results led to a lively discussion on the origins of CMEs and the mechanisms causing them, a discussion that is still going on.

SMM also carried the Active Cavity Radiometer Irradiance Monitor (ACRIM). It measured the solar radiation from the entire solar disk integrated over all wavelengths (total irradiance). For the first time it became possible to measure variations in the solar radiation with time and thus with solar activity. This objective had been pursued from the ground for several decades, without reaching any definitive results (see also SOLAR TELESCOPES AND INSTRUMENTS: GROUND). However, with ACRIM the required accuracy of 0.1% was more than achieved. ACRIM later flew on several space shuttle flights and on the UARS satellite, where it is still in operation. Instruments supplementing ACRIM and giving similar results have been the less accurate ERB on the Nimbus 7 satellite and its successor ERBE.

ACRIM on SMM and in later flights have produced several exciting new results. These include the first unambiguous detection of a decrease in total solar irradiance when a large sunspot crosses the visible solar surface, the so-called 'sunspot deficit'. A corresponding 'excess' effect has also been demonstrated for active regions with large facular areas. Finally, ACRIM has found that the total solar irradiance varies with solar activity, showing a maximum in the period of highest solar activity around year 1990 and minima in 1986 and 1996. Typical rate of change is 0.015% per year. A possible real increase of 0.0036% per year between irradiance minima in 1986 and 1996 is less certain.

The 1990s

The 1990s have seen two extensive and very successful solar space observatories, the Japanese Yohkoh satellite, with US and UK collaboration, and SOHO, a collaboration between the European and US space organizations, ESA and NASA, with ESA as the main partner. The objective of Yohkoh is to study the high-energy radiation from solar flares as well as quiet structures and pre-flare conditions. The instruments on SOHO investigate physical conditions from the innermost core of the Sun to its outer corona and the heliospheric space. Two factors have particularly added to the quality of solar physics from Yohkoh and SOHO data. The first is the open data access and the collaborative spirit of the investigators. Secondly, the real improvement of SOHO and Yohkoh over earlier missions comes more from the high time resolution and continuous

coverage than from the modest increase in instrument resolutions.

The Upper Atmosphere Research Satellite (UARS), launched in September 1991 and still in operation, is intended for studies of the Earth's atmosphere but contains relevant solar instruments. ACRIM has been mentioned. SOLSTICE and SUSIM on UARS observe the solar ultraviolet spectrum from 112 nm to 440 nm. The emphasis is on highly accurate absolute calibration that is stable over several years. The record from SOLSTICE and SUSIM constitutes a reference spectrum of the full Sun in ultraviolet and its variation with solar activity.

The main instruments on Spartan 201 are an Ultraviolet Coronal Spectrometer (UVCS) of the type flown on SOHO, and a coronagraph observing in the visual wavelengths. Spartan 201 has flown on five occasions between April 1993 and October 1998, partly supporting observations with Ulysses and SOHO.

Ulysses was launched in October 1990 (see SOLAR WIND: ULYSSES). It is the first satellite to investigate solar and heliospheric conditions at high solar latitudes. It carries no instruments for remote sensing of the Sun, as had been the original plan, but registers heliospheric magnetic fields, plasma waves, dust and solar wind particles, their speed, composition and stage of ionization. The trajectory of Ulysses first took it to Jupiter, where the gravity of the planet accelerated the satellite out of the ecliptic plane and into an orbit at nearly 90° inclination with the ecliptic. Ulysses passed over the south solar pole in June–November 1994 and over the north pole a year later, near solar activity minimum. The measurements showed the well-known slow solar wind, velocity 400 km s⁻¹, at low latitudes. However, at latitudes above 30° this was replaced by the fast solar wind, with a speed of 750 km s⁻¹ or more. To the fast winds from equatorial coronal holes had now been added a fast wind streaming out of the coronal holes in the polar caps. Furthermore, this wind fanned out quickly above the solar surface and extended to latitudes much lower than the borderlines of the polar coronal holes, lying near 60° latitude. The magnetic fields from the Sun must similarly fan out in the heliosphere. It will be interesting to see what Ulysses will register on its second pass over the poles in 2000–1 at maximum solar activity when polar coronal holes will be more 'filled in'.

A final mission in the 1990s was the Transition Region and Coronal Explorer (TRACE), launched in April 1998. TRACE observes the solar corona with an unprecedented angular resolution, 1 arcsec in the temperature range from 1 MK to 2.5 MK. The solar emission is observed in EUV wavelength bands centered at 17.1 nm, 19.5 nm and 28.4 nm. Other wavelength channels isolate emission from the chromosphere (10 000–30 000 K) in Lyman alpha from hydrogen, in the resonance lines from three-times ionized carbon at 155 nm (100 000 K) and in the near ultraviolet and white light continuum.

The future

Plans for the future are many and for most part uncertain. The Japanese SOLAR-B satellite is a likely project, scheduled

to be launched in 2004. This satellite will contain a visual telescope to measure photospheric magnetic fields with extremely high spatial resolution and ultraviolet and x-ray telescopes to measure and monitor the coronal emission. The mission aims at understanding the detailed relationship between magnetic fields and coronal heating and emission in the Sun.

NASA has sketched an entire 'road-map' of satellites. Only a few of these are likely to fly and at present none is securely financially confirmed. Interesting possibilities include a solar probe, going to 4 solar radii to make *in situ* observation of the acceleration region of the solar wind, and Stereo, which will be a pair of satellites flying in the Earth's orbit around the Sun at a significant distance in front of and behind the Earth. The stereoscopic view of solar and heliospheric phenomena will allow a three-dimensional mapping of CMEs.

Europe and ESA are considering a solar orbiter, flying at 45 solar radii from the Sun, and in an inclined orbit to the ecliptic reaching heliographic latitudes of 40° . These plans are still at a preliminary stage, and joining the US in a continuation of SOHO with instruments having super-high resolution should also be considered.

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